1 Introduction

After initial data taking in 2002 and moderate data taking in 2003, the year 2004 was particular important for COMPASS. The goal to roughly double the amount of data taken in 2002 and 2003 was largely achieved despite a difficult beam startup in 2004. After a long muon run, a hadron pilot-run was performed during the last weeks of the 2004 run. The spectrometer performance with a pion beam could be studied and, in addition, enough statistics was collected to improve significantly the previous results from Serpukhov on the pion polarisabilities. First physics results from the 2002 and 2003 muon data were presented at the 2004 conferences, particularly at the SPIN 2004 Symposium in Trieste. The first three physics papers on the structure function $g_1$, the Collins and Sivers asymmetries, and a pentaquark search are out. Preliminary results on the gluon polarisation from the light-quark indicate an unexpectedly small gluon polarisation around $x_g \approx 0.1$.

Our mid and long-term plans were presented to the special SPSC meeting in Villars and well received. One of the presented long-term perspectives was submitted as an Expression of Interest to the SPSC (SPSC-EoI-005), focusing on Generalised Parton Distribution functions (GPDs). A major concern remains the beam sharing between LHC, CNGS and fixed-target experiments in the years till 2010.
The year 2005 is dedicated to analysis and spectrometer upgrades for the 2006 run, which once more will focus on the $\Delta G/G$ measurement in the open charm channel. Significant improvements of the spectrometer performance is expected from the new large-acceptance target magnet, an ambitious RICH-1 upgrade and the completion of ECAL1 and a preshower detector.

## 2 The 2004 muon run

### 2.1 Data taking

The total number of scheduled days for the 2004 muon run amounted to 110 days from May 17 to October 4 excluding the machine developments. About four weeks were lost mainly due to two septum failures in the PS leaving 74 days of beam. The set-up time of the spectrometer could be reduced to three days of scheduled beam time, taking advantage of some early beam delivery from the SPS during its start-up phase. The COMPASS data taking efficiency was 86%. The target polarisation reversals and calibration runs limit it to about 90%. The only serious off-times were due to water leaks in the spectrometer magnet SM2 causing damage in some read-out electronics. The beam delivery efficiency was 73% not accounting for the lower intensity during the two weeks of single injection from the PS. In Figure 1 the efficiencies are shown period by period. In total 450 Tbyte of data were collected. The corresponding progress of data recording is shown in Fig. 2.
2.2 Spectrometer

As in 2003 the polarised target reached consistently deuteron polarisations above the design value of 50%. The additional detector plane in the beam momentum station increased the redundancy and thus the efficiency in the beam reconstruction. Three silicon stations were operated during the muon run and an addition GEM detector was installed to reinforce the scattered-muon tracking at the downstream end of the spectrometer. The straw detectors benefited from a reduced noise due to an improvement in the grounding scheme of the readout electronics. The full set of 24 planes of the large DW drift chambers was implemented for the 2004 run. The other tracking detectors remained unchanged with respect to the 2003 run.

Two of the eight RICH photon detectors were exchanged in the 2003/2004 shutdown, one by an entirely new chamber and the other by a refurbished one. Together with a nine-fold segmentation of the high-voltage distribution for each chamber this led to a largely enhanced and satisfactory electrical stability. All but two of the 72 sectors were at nominal high voltage. The oxygen and water contamination of the radiator gas was extremely low and of order 3 ppm and 1 ppm, respectively resulting in an excellent transparency.

To the 2000 lead glass blocks in ECAL2 additional 1000 blocks were installed and equipped with a newly developed, fully pipelined, flash-ADC read-out (SADC).

The software filter in the DAQ stream is now fully implemented and tested. For the muon runs it rejects around 20% of the events based on the number of hits in the
beam trackers, improving the trigger purity. Acquisition rates of 10 kHz were used routinely. In the hadron pilot run 20 kHz were used.

3 The hadron pilot run

At the end of the 2004 beam time (19 October – 14 November) data were taken with a 190 GeV/c $\pi^-$-beam. The main spectrometer modifications were in the target region, where the polarised target had to be removed. The tracking in the target region was reinforced by two additional silicon stations. The change-over took place from October 5 to 19 without any loss of beam time. After a commissioning and calibration period, physics data were taken from November 2 to 14 with 1.6 mm and 3 mm thick lead targets as well as carbon and copper targets. A similar amount of data were taken with a muon beam as reference, a unique possibility at the CERN M2 beam line. Due to a 10-times higher than expected trigger rate the maximum acceptable acquisition rate of 80k events/spill was reached at a beam intensity of $5 \times 10^6$ particles/spill, a factor two less than originally planned. The reason is partly understood. A more elaborate trigger and less material in the beam line will improve the situation in the future. The progress of data taking is shown in Fig. 2. As a consequence of analysis priorities data processing of the full data set has just started now. A first look at the Primakoff reaction $\pi$ Pb $\rightarrow \pi^' \text{Pb} \gamma$ is shown in Figs. 3 and 4, where the data and reconstruction quality is demonstrated by the vertex distribution of the interaction vertices and the clean $t$-distribution. Cuts were applied to the energy balance at the vertex ($\pm 25$ GeV), the momentum transfer $t < 1.5 \times 10^{-3}$ and the $\gamma\pi$ invariant mass ($< 465$ MeV) to eliminate exclusive $\rho$ production. From the small fraction of data processed so far, we estimate the total statistics to 30000–40000 Primakoff events after all cuts, corresponding to at least four times that collected by the previous Serpukhov experiment.

At the end of the pilot run a short high-intensity test with $10^8 \pi$ /spill was performed to study the spectrometer and detector performance in this environment. No obvious detector limitations were discovered.

In summary, the hadron pilot run yielded good physics data and proved the princi-
ple of the hadron spectrometer set-up. On the other hand it has revealed some weaknesses, which can now be eliminated well before a full hadron production run.

4 Status of physics analysis

4.1 Gluon polarisation

Information on the gluon polarisation at COMPASS is obtained from the longitudinal double-spin cross-section asymmetries. The contribution arising from the photon–gluon fusion process (PGF) $\gamma^* g \rightarrow q\bar{q}$, is proportional to $\Delta G/G$. For heavy (charmed) quarks the scale is given by the charm mass $m_c$, while for the light quarks the transverse momentum of the produced quarks $p_T^2$ must ensure the hardness of the process. For the light-quark case we require two hadrons in the final state and analyse separately event samples with $Q^2 < 1 \text{ GeV}^2$ and with $Q^2 > 1 \text{ GeV}^2$. In addition we took a first look at an event sample which requires only one hadron in the final state. For the latter process a full NLO calculation in photoproduction is available [2].

The determination of $\Delta G/G$ from the light-quark data sets depends on Monte Carlo simulations to obtain the fraction of PGF processes in the event sample. Events were selected with $p_T > 0.7 \text{ GeV}$ for both hadrons individually and with $(p_{T1}^h)^2 + (p_{T2}^h)^2 > 2.5 \text{ GeV}^2$. For the event samples with $Q^2 > 1 \text{ GeV}^2$ and $Q^2 < 1 \text{ GeV}^2$ the Monte Carlo codes LEPTO and PHITIA were used respectively. The parameters of both codes were tuned to reproduce our data and varied to determine the systematic errors. For the sample with $Q^2 < 1 \text{ GeV}^2$ special care was taken of the contributions from resolved-photon processes. Since the polarised parton distributions in the photon are unknown, minimal and maximal scenarios [3] were studied. It turned out that the difference between the gluon polarisations extracted in the two scenarios from our data is limited. This new result allows us to use also this high-statistics sample to study the gluon polarisation.

The preliminary results obtained from the 2002 and 2003 data are

$$\Delta G/G = 0.06 \pm 0.31 \text{ (stat.)} \pm 0.06 \text{ (syst.)},$$

for the $Q^2 > 1 \text{ GeV}^2$ sample (see e.g. Ref. [4]) and

$$\Delta G/G = 0.024 \pm 0.089 \text{ (stat.)} \pm 0.057 \text{ (syst.)}$$

for the $Q^2 < 1 \text{ GeV}^2$ sample.

These independent results show consistently a small gluon polarisation around $x_g \simeq 0.1$. In Figure 5 our results are compared to the values obtained by HERMES [5] for all $Q^2$ and by the SMC for $Q^2 > 1 \text{ GeV}^2$ [6].

The open charm data samples of 2002 and 2003 have been fully analysed in terms of cross-section asymmetries. However, a significant result for $\Delta G/G$ can only be obtained including the 2004 data. Most of the information is coming from $D^0$'s originating from $D^+$ decays. This is because of the strong background suppression by
Figure 5: Direct measurements of $\Delta G/G$ and predictions from Ref. [1]. The horizontal bars indicate the $x_g$ ranges probed by the measurements. Only statistical errors are shown.

requesting the additional slow pion form the $D^*$ decay. The data sets for directly produced $D^0$'s not stemming from a $D^*$ decay and those $D^0$, where the decay-kaon momentum is below the Cherenkov threshold are also included in the analysis chain. Figure 6 shows the $K\pi$ invariant mass distribution for $'D^*$ events' from 2003. From the 2002 and 2003 runs we have about 1500 $D^*$ events. The excellent agreement of the measured and simulated $z$-distributions for $\gamma^* g \rightarrow c\bar{c}$ events demonstrates that indeed PGF processes dominate our event sample (Fig. 7).

Figure 6: Invariant $K\pi$ mass for $'D^*$ events from 2003.

Figure 7: Comparison of the $z$-distributions from data and Monte Carlo.
Figure 8: Collins asymmetry (top) and Sivers asymmetry (bottom) against $x$, $z$ and $p_T$ for positive (full points) and negative hadrons (open points). Error bars are statistical only. The first column gives the asymmetries for all hadrons, the other three columns for the leading hadrons. In all plots the open points are slightly shifted horizontally with respect to the measured value [7].

4.2 Single-spin transverse asymmetries

The single-hadron analysis of the 2002 data with transverse target spin orientation is finalised and accepted for publication [7]. The Collins asymmetries, which are related to the transversity quark distributions $A_1$, and the Sivers asymmetries, which are related to intrinsic transverse momentum $C_T$ of quarks in the nucleon are shown as function of several kinematic variables in Fig. 8. Our data represent the first information on the transverse asymmetries of the deuteron in the DIS region. Effects are small and consistent with zero within the present accuracy of the data. The analysis of the 2003 data is essentially finished, but still require some cross-checks for the systematics errors. The total statistics accumulated in 2002–2004 is more than an order of magnitude larger than that of 2002.

The measured Collins asymmetries are proportional to the product of a fragmentation function and a parton distribution function ($A_1$). It cannot be excluded that this spin-dependent fragmentation function is small in this particular process and thus responsible for the small asymmetries. Therefore other quark polarimeters are being investigated like the interference fragmentation function [8] which involves two-hadron correlations. Preliminary results from the 2002 and 2003 data will be shown at the DIS2005 conference. Another interesting observable related to $\Delta_T q$ is transverse $\Lambda$ polarisation, which is also being studied.
4.3 Deuteron structure function $g_1$

The analysis of $g_1$ for the 2002–2003 data in the region $1 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2$ and $0.004 < x < 0.7$ is published [9]. The new data are the most precise data in the region $0.004 < x < 0.03$. We performed a next-to-leading order QDC fit in the $\overline{\text{MS}}$ scheme to study the impact of our data. The fit includes all previous data points for the proton, deuteron and neutron from CERN, SLAC and DESY as well as the recent neutron data from JLab at large $x$. It is evident from Fig. 9 that the COMPASS data are in better agreement with the fitted $g_1$ structure function, even when not included in the fit. We quote the effect on the first moment $\Delta \Sigma$ of the flavour singlet distribution at $Q^2 = 4 \text{ GeV}^2$, which in the $\overline{\text{MS}}$ scheme is identical to the flavour-singlet axial charge $a_0$. The result including the COMPASS data is $a_0 = 0.237^{+0.024}_{-0.020}$ and omitting the new data we obtain $a_0 = 0.202^{+0.042}_{-0.077}$. Thus COMPASS data reduce the uncertainty of this important physical quantity by a factor two. The new data were already taken into account in new global analyses [10].

4.4 Other analysis topics

Recently NA49 reported an exotic baryonic state at a mass of 1862 MeV decaying into $\Xi^-\pi^-$ which had been interpreted as pentaquark. Motivated by this observation
we searched for narrow \( \Xi^{-\pi^\pm} \) and \( \Xi^+\pi^\pm \) resonances produced by quasi-real photons. While the ordinary hyperon states \( \Xi(1530)^0 \) and \( \Xi(1530)^0 \) are clearly seen, no exotic baryon is observed in the data taken in 2002 and 2003 [11].

We also study longitudinal spin transfer in \( \Lambda \) and \( \bar{\Lambda} \) production, which can e.g. give hints on the strange quark polarisation in the nucleon. The results from the 2002 data are shown in Figs. 10 and 11 in comparison with previous results [12]. Also transverse \( \Lambda \) polarisation is investigated.

The analysis of the spin density matrix elements in exclusive \( \rho \) production is almost finalised.

The reconstruction of the 2004 data is far advanced. The production of the transverse data (20%) is finished and that of the longitudinal data (80%) is about half-way. The mass reconstruction of the data from the hadron pilot run is just starting. Four of the five periods from 2002 were already reprocessed, yielding about twice as many \( D^+ \)'s as in the first production, due to improvements in the code.

## 5 Upgrade of the spectrometer

### 5.1 Polarised target solenoid and new drift chamber

The target solenoid has been reconstructed at Oxford Danfysik (OD). An agreement between OD, Saclay and COMPASS has been worked out to allow the final tests to be done on Saclay premises under the responsibility of OD. The cryogenic infrastructure at Saclay is much more adequate for these tests than that at OD. The magnet was delivered end of 2004 and set up at Saclay during January and February 2005. About two months were lost due to a leak which appeared after the first cool-down of the magnet. This has now been fixed and the magnet is again cooling down. First energising of the magnet is expected for mid to end May 2005. Thus the project will be in time for
the 2006 run, if no major new problems appear. The acceptance increase with the new magnet system for the open-charm measurement ($D^*$) corresponds to a factor 1.3 in data-taking time.

At Saclay a new drift chamber, similar to DC1 – DC3 is being built. This chamber will replace the drift chamber downstream of SM1, which is too small for the acceptance of the new magnet and will be needed upstream of SM1.

5.2 RICH-wall pre-shower and ECAL1

A new large-area tracker will be set up between RICH-1 and ECAL1, the so-called RICH-wall detector. Such a tracker is already part of the COMPASS proposal, but due to the lack of resources was not included in the initial layout of the MoU. The system is very similar to the MuonWall-I, Iarocci-like detector. The chambers were built at Dubna with INFN funding and the read-out electronics is developed in Torino. This detector will be interleaved with lead sheets and will serve also as preshower for the ECAL1. The tubes for the detector were delivered to CERN in April 2005. It will be fully available for the 2006 run.

A new layout for the arrangement of the lead glass in ECAL1 was suggested in which the detector could be operational in its full acceptance for the 2006 run. While the good granularity is kept for the central region, it will be reduced by a factor four in the intermediate region. This loss of spatial resolution can be recovered by the information from the preshower detector. Detailed studies are still ongoing, but this scenario looks very promising. The needed additional 1500 channels of the new SADC read-out are being constructed and will be available for the 2006 run.

An interesting perspective is the reconstruction of the $D^0$ from its $D^0 \to K\pi\pi^0$ decays with a branching ratio of 10%. Monte Carlo studies indicate that using ECAL1 a big fraction of these events can be reconstructed. A comparison of data and Monte Carlo is ongoing for the 2004 data using ECAL2 only.

5.3 RICH-1

A major upgrade of the COMPASS RICH-1 detector system, based on Multi-Anode Photo-Multiplier Tubes for the central region and on APV analog sampling chip read-out of the existing CsI multiwire proportional chambers for the outer external region is ongoing. The main results from the R&D, prototyping and testing activities are described in a COMPASS note attached to this document as Appendix A. It discusses the improvements in particle identification and the technical solutions. The upgraded RICH-1 will match the challenges coming from the COMPASS physics programme foreseen for the next years.

A large fraction of the financing was requested to INFN by Trieste and Torino. The evaluation was favourable and INFN approved the project with a spending profile, which allows us to implement to project for the 2006 run. The funding of the APV
ADC readout for the outer region is covered by Saclay and TU Munich. Also this part will be implemented for the 2006 run.

The impact on the precision of the physics measurements depends strongly on the illumination of the RICH detector for a specific process. The analysis is difficult and still ongoing. For the measurement of $\Delta G/G$ from open charm, we expect a factor 1.6 in terms of equivalent events (figure of merit).

6 Running strategy

The Collaboration has decided to entirely focus on muon running in 2006, starting with about 100 days of longitudinal runnig for $\Delta G/G$ using a polarised deuteron target. Detailed estimates of the effect of the hardware improvements for the open-charm measurement indicate that the precision from the 2006 run alone should be better than that of the 2002–2004 data taking.

The last 30 days of the 2006 run will be dedicated to transversity with a polarised proton target made of $\text{NH}_3$. Here larger effects are expected than for the deuteron, both from theory and the preliminary HERMES results. For a flavour separation of the quark distributions, proton and deuteron data are needed.

The target change-over will take 1–2 weeks. We request to schedule the 25 ns SPS runs in 2006 accordingly. These periods cannot be used for data taking by COMPASS.

For 2007 COMPASS will switch to hadron data taking.

7 Summary

COMPASS muon data taking in 2004 and the hadron pilot run were fully satisfactory. The analysis is well advanced and the first three physics papers are published. The knowledge of the spin-dependent structure function $g_1^d$ was improved considerably at small $x$. The first results on transverse spin effects of the deuteron in DIS are compatible with zero within statistical uncertainties. With a good statistical significance, we can exclude the existence of the $\Phi(1860)$ in our leptoproduction sample. The results on $\Delta G/G$ from hadron pairs show a surprisingly small gluon polarisation and represent the most precise data on this important quantity. The open-charm measurement still lack statistics. With the ongoing ambitious upgrades of the spectrometer we expect to at least double the data in this channel in the 2006 run. In the following years the focus of COMPASS will shift to the hadron programme.
References


A  APPENDIX: Proposal for an upgrade of the COM-PASS RICH-1 detector
PROPOSAL FOR AN UPGRADE OF THE COMPASS RICH-1 DETECTOR

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Abstract

A major upgrade of the COMPASS RICH-1 detector system, based on Multi-Anode Photo-Multiplier Tubes for the central region and on APV analogue sampling chip read-out of the existing CsI Multiwire Proportional Chambers for the external region is proposed. The main results from the R&D, prototyping and testing activities are presented. The expected improvements in particle identification performances are discussed. The upgraded RICH-1 will match the challenges coming from the COMPASS Physics programme foreseen for the next years.
1. INTRODUCTION

The second phase of data taking for COMPASS is expected to start in 2006 and will continue at least until 2010. During this period COMPASS should achieve an accurate measurement of the gluon contribution to the nucleon spin $\Delta G/G$, and complete the remaining parts of its proposed muon and hadron programmes [1]. A successful achievement of these goals requires stable and fully efficient spectrometer performances, even for the higher muon or hadron beam intensities (up to $10^8$/sec) that are planned for the next years and the challenging trigger rates (up to a maximum of 100 kHz) foreseen for Primakoff and charm spectroscopy studies.

Good particle identification (PID) is necessary for both the spin structure of the nucleons and the charm spectroscopy studies. In particular, hadron identification is crucial; due to the event complexity, COMPASS, for its spectrometer, has selected RICH detectors.

RICH-1 has been in operation since 2001 and has collected data between 2002 and 2004. Following several improvements, it has reached its plateau performances with the present detection and read-out system in 2003. Excellent gas transparency, constant over a large period of time has been achieved. Operation of the CsI-MWPC photon detectors has been carefully optimised. Constant monitoring of all relevant parameters has been implemented and is routinely used in the data analysis.

For very forward particle trajectories, RICH-1 performances are reduced due to the presence of central dead zones and due to the large dispersed halo that comes along with the muon beam. Combined with the long memory time of the present photon detectors readout electronics, this halo generates high pad occupancy in the central region of the detector, resulting in a deteriorated signal over background ratio. For both central and outside region chambers the far-halo minimum ionising particles that traverse the CsI-MWPCs increase the probability for electrical instabilities in the photon detectors; this limits the maximum achievable gain and consequently the number of measured photons.

Originally, the COMPASS RICH project included two RICHes, namely RICH-1 and RICH-2. RICH-2 was designed to perform hadron PID at momenta larger than about 50 GeV, and to complement RICH-1 in the small angle region. Its construction is not foreseen till the end of the present decade. Thus, in the present spectrometer configuration with RICH-1 taking care of the whole hadron PID, an increase of the RICH-1 PID ability towards higher momenta and for particles scattered at small angle could help for more efficient particle detection.

The prospects for using the COMPASS spectrometer at increased muon and hadron intensities and trigger rates in the next years also lead us to a re-examination of the pad occupancy and the acquisition dead time as a function of the expected trigger rates. It appears that an improvement of the readout time resolution by a large factor is mandatory. The dead-time of RICH-1 read-out, although acceptable up to now, could also rapidly become a limiting factor.

All these considerations suggest an upgrade of RICH-1: the instrument, already largely contributing to COMPASS physics measurements, can provide improved performances after upgrading various aspects of the photon detection system.

We propose a RICH-1 Upgrade Project, made out of two complementary technologies. In the most central region of the detector, a replacement of both the detection method and the read-out scheme is foreseen. The use of Multi-Anode Photo-Multiplier Tubes (MAPMT) should lead to a significant increase in the number of detected photons, thus enlarging the momentum range in which efficient PID is performed. The associated read-out system is dead time less.
In the remaining part of the detector, the use of APV-based read-out architecture, should allow an important reduction of the electronics dead time and improved time resolution, while making a cost-effective use of the existing MWPC-CsI detectors.

The overall RICH-1 Upgrade Project thus aims at much improved RICH-1 performances, with substantially increased PID power in an enlarged momentum range in the central region and, on the whole active surface, with largely increased time resolution and an efficient dead-time reduction at moderate and high trigger rates.

2. THE RICH-1 DETECTOR

2.1 RICH-1 Design

The COMPASS RICH detector has been designed [2-6] to efficiently identify kaons and pions for momenta of up to about 50 GeV/c and for horizontal and vertical acceptances of 250 and 180 mrad respectively. The large acceptance results in large transverse dimensions of all the detector components. In order to identify particle with energies of up to several 10 GeV/c, the 3 m long radiator vessel is filled with ~ 80 m$^3$ perfluorobutane (C4F10) gas. A large (~21 m$^2$) mirror wall reflects the Cherenkov photons and focuses them on to the photon detectors with a total of 5.3 m$^2$ sensitive surface. The detector was designed in the mid nineties and makes use of the most updated photon detector technique available in those days to cover large detection surfaces at affordable economic costs, namely MWPCs with CsI photocathodes, developed at CERN by RD26. RICH-1 CsI-MWPC set is the largest CsI photon detection system in operation so far. The detectors are composed of photocathodes consisting in PCBs coated with a CsI layer acting as photon converter and MWPC electron detectors. The photocathodes are segmented into 82 944 8x8 mm$^2$ pad channels.

The CsI quantum efficiency is non zero in the VUV region only, namely below 200 nm. This imposes severe constraints on several detector components: mirrors, photon detector windows, gas purity and vessel construction In particular, fused silica plates, with light transmission of ~50% at 165 nm have been chosen as photon detector windows. Thus, the RICH-1 detector operates in the 160-200 nm wavelength range.

The front-end electronics is based on a modified version of the front-end chip Gassiplex, also developed in the context of RD26, as well as on a dedicated read-out architecture with large distributed intelligence. The detector pixels are read out by 192 front-end cards with 432 channels each.

2.2 Hardware status

After the COMPASS technical run in 2001, during which RICH-1 was not yet entirely equipped, in 2002, 2003 and 2004 COMPASS has collected polarised DIS data with RICH-1 fully completed. The detector has reached stable plateau performances in year 2003, later confirmed in 2004, after numerous improvements have been implemented. These include:

- Accurate MWPC construction or refurbishing. CsI-MWPCs when operated in radioactive environment, as in the COMPASS spectrometer, exhibit electrical instabilities, that appear in the vicinity of tiny local defects, with long (~1 day) recovery time after a trip episode. Accurate MWPC construction and later refurbishing allowed us to minimize the effect. In the test run of 2001 only 25% of the MWPCs area was stable; in 2002, 75%; in 2003 and 2004, 97%. Nevertheless, the level of radioactivity in the CsI-MWPC location prevents us to operate photon detectors at gains larger than ~4 x 10$^4$. This gain, combined with an effective threshold level of ~
3500 Equivalent Noise Charge (ENC, or $e^-$), results in efficiency for the detection of single photoelectrons of about $\sim 65\%$.

- Good transparency of the gas radiator, stable over months. A transmission rate of 80% at 160 nm through 187 cm of gas at atmospheric pressure is achieved since 2003, after a more efficient method for raw gas cleaning was applied and an improved on-line gas filtering was put in operation. Moreover, the gas leakages have been reduced to less than 100 liters at atmospheric pressure per day, thus keeping the gas mixture stable and rich in $\text{CF}_{10} (\geq 95\%)$.

- Minimized electronics noise level. The read-out electronics noise was reduced from $\sim 2000 e^-$, typical figure in 2001, to $\sim 1000 e^-$ by modifying the grounding of the front-end boards.

- An improved algorithm for RICH pattern recognition and PID implementation allowed us to minimize the background effect, with important PID improvements for particles with small angle trajectories.

The read-out architecture has been designed so to allow dead-timeless operation up to about 100 kHz trigger rate. The digital part of the read-out system fulfills this design parameter. One limitation comes from the characteristic of the Gassiplex chip: after receiving a trigger, the output baseline is shifted and its restoration required about $\sim 3-5 \mu s$, resulting in a corresponding dead time, which can seriously affect the experiment luminosity at high trigger rates.

2.3 Performances

In the COMPASS environment the RICH-1 performances [7] may vary according to the particle phase space region considered. Several RICH properties (number of photons, background, etc...) strongly depend on the polar angle of the incident particle. For small polar angles the ring images are formed in the central zone of the detector. In this region the overall performances are somewhat reduced due to two main reasons.

First, in order to avoid that the photons from the beam particles reach the photon detector, a beam pipe is present as well as a corresponding hole in the mirror wall detectors. As a result a small central dead zone is created and the number of photons is reduced accordingly.

Second, the presence of relevant background from uncorrelated events, mainly particles of the huge dispersed halo that accompanies the muon beam, decreases the signal over background ratio. This physics background comes from the long memory time of the CsI-MWPC coupled to the Gassiplex, and is mainly due to the FE chip.

The number of detected photons $N_\gamma$ per ring at saturation is $\sim 14$, except in the most central region: for polar angle below 30 mrad, this number is $\sim 10$.

The resolution in the measured Cherenkov angle for a single photon is 1.1 mrad everywhere while the resulting resolution from all the photons of a ring does not scale with the number of detected photons due to the presence of the background; for instance, it is $\sim 0.45$ mrad for particles with polar angles larger than 30 mrad and selected in momentum so that the mean number of detected photons is larger than 11.

The overall performance of the RICH detector is indicated by its ability to efficiently detect and unambiguously identify kaons and pions. Both efficiency and purity vary as a function of the phase space considered and of the particular physics process involved. When selecting the D0 process from its decay to $K$ and $\pi$, both particles are detected by the RICH. The product of its efficiency and purity, as indicated by the Factor of Merit (FoM) of the RICH is about 0.55.
The FoM for the $K^0$ coming from $D^0$ and $\bar{D^0}$ decay, as estimated by a Monte-Carlo simulation that fits the data is 0.45. Within the corresponding errors the two estimates are in good agreement.

3. PHOTON DETECTION BASED ON MAPMTS

We are developing a system based on MAPMTs and lenses for fast photodetection to overcome the challenges due to the high background level from uncorrelated events in the central region of RICH-1; the implementation of a dead-time less read-out system will allow us to match the needs of increased beam intensity and trigger rate in COMPASS.

The system is proposed for the central part of the RICH-1 photon detectors, namely to replace the 4 central photocathodes of the CsI MWPCs, corresponding to 25% of the total active surface.

The approach with MAPMT and lenses is not new (HeraB, studies LHCb); in our design, we increase the ratio of the entrance lens surface and the PMT photocathode surface to reduce the number of PMTs and thus keeping the system at affordable cost. With the proposed two lenses telescope, the effective pixel size is 12x12 mm$^2$. We extend the detected portion of the Cherenkov light spectrum to the UV domain (down to ~ 200 nm) by using UV extended MAPMTs and fused silica lenses.

For the photon detection system we have selected the R7600-03-M16 MAPMPT developed by Hamamatsu, characterized by bialkali photocathode with 18 x 18~mm$^2$ active surface, 16 pixels, and an UV extended glass entrance window. Homemade resistive dividers formed by thin, light tight PCBs are mounted onto the bare MAPMTs. Various fused silica lens systems coupled to the MAPMTs have been considered: (i)–single, thick plane-convex lenses to minimize the telescope length, used in test beam exercises and (ii)–two-lens system to minimize image distortions, so to increase the effective detector resolution and to increase the geometrical acceptance: this is the chosen configuration.

The MAPMT are read with an amplifier /discriminator derived from MAD4 discriminators, housed on small front-end boards mounted directly onto the resistive divider boards. Power and threshold are distributed via deck PCB, while digital F1 boards are directly coupled to the deck boards; the arrangement is without cables, very compact and reliable. The read-out architecture is similar to that already successfully implemented in COMPASS for various detectors (MWPCs, W45, MuonWall-1) and in preparation for the RICH Wall.

The photon detection principle has been validated in two test beam periods, of increasing completeness, at the CERN PS beam line T11 in summer 2003 and 2004.

The results of the tests show that the R7600 photomultiplier coupled to the MAD4 chip can detect single photoelectrons with full efficiency. The long plateau of the threshold curves clearly indicates that noise and crosstalk can be efficiently rejected without photoelectron losses.

The number of detected photoelectrons has been compared with Monte Carlo estimates in different data taking conditions:

- In configurations without lenses, the number of detected photoelectrons is well reproduced by Monte Carlo. Agreement between Monte Carlo and measured number of photoelectrons is also obtained in configuration with lenses: the lens effect is correctly reproduced and can be used for realistic simulation of more complex set-ups.
- Assuming the overall scale factor from data collected without lenses, a complete agreement between Monte Carlo and measured number of photoelectrons in configuration
with lenses is obtained: the lens effect is correctly reproduced and can be used for realistic simulation of more complex set-ups.

More details about the test beam results can be found in Ref. [8]

The main features of the final design of the system for COMPASS RICH-1 are:

• The replacement of one of the two photocathodes of each of the four central MWPCs with a panel housing 144 UV extended, 16 channel MAPMTs and the associated fused silica lens telescope (one telescope per PMT). The anode wires in front of the lens and PMT panel will be removed: this is obtained by producing new anode frames with half-length wires. The other MWPC components are unchanged. The electrical stability test of the modified chambers (half-length wires and panel with lenses) is ongoing at GIF.

• A read-out system based on the amplifier/discriminator MAD and the F1 TDC, similar to the arrangement already implemented for the 2004 test beam set-up.

• The design of C-MAD, a modified version of MAD4 is on-going. It will be a CMOS, 0.35 µm chip, with 8 channels with independent setting of the threshold and with increased input rate capability. The first prototypes will be delivered within February, iteration is foreseen in Summer 2005 and the production can be submitted at the end of 2005. The C-MAD cannot be available for the 2006 run: the existing MAD4 will be used.

• The F1 chip in TDC mode will be used; the analysis of the expected rates and thus the expected background level suggest that with a time window of ~2ns a substantial gain with respect to the latch mode architecture is achieved: almost no physical uncorrelated background is expected.

• A telescope of two fused silica lenses, a spherical one cut in rectangular shape so to match the surface of the telescope entrance window, and a smaller aspherical one, placed in front of the MAPMT, has been designed. The telescope axis will be inclined, so to match the average direction along which the Cherenkov photons impinge onto the lenses. This approach has been preferred to the one with single, ticker lens, not only because of the smaller image deformation and the lower chromaticity, but also because the resulting dead zones between telescopes can be as small as ~2%.

• A support panel, compatible with the mechanical structure of the present photon detectors, the two-lens telescope, the minimum dead zones between telescopes and the requirement of inclined telescope axis has been designed.

The main features of the expected performances compared to the ones of the present photodetection system are:

• A number of detected photons per ring at least a factor 3.5 larger than the present one; at saturation, and far from the central region affected by dead zones this will result in ~ 50 photons per ring.

• The resolution on the measured Cherenkov angle from single photon will be worsened by a factor ~1.5, due to the enlarged pixel size as imposed by economical reasons. This effect is largely compensated by the increased number of detected photons; in addition the resolution also benefits from the negligible uncorrelated background level. The expected resolution from a whole ring at saturation, and far from the central region affected by dead zones is ~ 0.3 mrad (presently 0.45 mrad) or better. This
resolution makes possible $\pi/K$ separation at $2.5 \sigma$ for up to more than 50 GeV/c, to be compared with the present limit of 40 GeV/c.

- The increased number of detected photons will lower the effective RICH threshold; the new thresholds almost coincide with the physical thresholds of the Cherenkov effect. For instance, the present threshold for kaons is $\sim 2$ GeV/c higher than the threshold of the Cherenkov effect.

- Monte-Carlo simulations with the parameters of the proposed system were made. The expected efficiency for the product of photon conversion and photoelectron detection is conservatively reduced by 15%. They indicate sizeable increase of both purity and efficiency leading to an expected factor of merit of 0.85 or better for the D0 channel, to be compared with 0.45, for the present RICH detector.

The design is final; a general schedule has been set, including prototyping, production and assembly. Constructions will be completed within the end of 2005 and installations will take the first trimester of 2006.

The cost estimate is almost final; the total resulting cost is $\sim 1.2$ M\(\text{€}\) and about 25% of that cost is already covered. For the remaining part, the submission of a financing request is ongoing.

4. ANALOG SAMPLING READ-OUT SYSTEM BASED ON THE APV CHIP

A new sampling read-out system based on the APV chip was developed for RICH-1. The time information of the new system will allow us to reduce the effective time gate of the RICH read-out from 3-5 $\mu$s to 400 ns, leading to a large suppression of the uncorrelated background. The system significantly reduces the read-out dead-time, making it similar to the rest of the experiment, i.e. 5% at 50 kHz trigger rate. The new read-out system will equip 12 out of the 16 photo-cathodes, which represents 62208 channels (75% of the present RICH read-out).

The new read-out system is based on the APV25S1 chip. The chip is a 128 channels preamplifier/shaper ASIC with analog pipeline, originally developed for the CMS Silicon microstrip tracker [9], and successfully adapted for the COMPASS Silicon [10] and GEM [11] tracking detectors. Each channel consists of an inverter stage with unit amplification to allow signals of both polarity to be processed, and a CR-RC type shaping amplifier. Its time constants are adjustable in a wide range from 50 to 500 ns by feedback transistors, opening the possibility to use the APV to read “slow” detectors as MWPCs. The amplifier output amplitudes are sampled at a frequency of 40 MHz and stored in a 192 cells analog pipeline. Upon arrival of an external trigger at the chip, in order to reconstruct the shape of the signal and thus get information on the timing, three samples are read, at the beginning, at the rising edge and at the peak of the signal. The time gap between consecutive samples can be varied in steps of 25 ns; for the COMPASS RICH-1 MWPC detectors the optimal sampling was found to be 150 ns. The multiplexed information from the APV chip is digitized using a flash ADC. An FPGA then performs online zero suppression by applying individual thresholds for each channel. One of the APV chip feature is a possibility to run the multiplexer either with 20MHz or 40MHz clock. The measurements were done while running the multiplexer with a 20MHz clock. For the final operation it is foreseen to push it to 40MHz in order to keep the dead time at the expected value.
In order to match the external constraints coming from the lay-out of the present RICH-1 front-end boards, four APV chips are mounted on one APV front-end card, each APV reading 108 RICH pads. Three APV front-end cards are then connected via a dedicated adapter card to one ADC module, allowing the use of the same electronics modules as those used for the readout of the COMPASS GEM and Silicon detectors.

A full test of the proposed read-out system was performed in nominal beam conditions in the central region of the RICH. A total of 12 APV front-end cards, corresponding to half the area of one photon detector were used. For the optimal APV setting the measured average noise figure is 640 e$^-$, compared to the value of $\sim$1000 e$^-$ for the Gassiplex chip. The spectrum of photons from RICH-1 was then used to determine the mean photon amplitude, after applying a conservative cut at 2400 e$^-$. Due to rounding of each threshold value to the smaller integer number the effective threshold applied was between 2.5 $\sigma$ and 3 $\sigma$ only. This feature will be avoided in final ADC modules by using 12 bits resolution ADC chips. The resulting mean photon amplitude value of $\sim$5800 e$^-$ is somewhat lower than the Gassiplex value of $\sim$8800 e$^-$, a feature quantitatively explained by the ballistic deficit coming from its shorter time constant. Due to its lower noise figure the APV can be operated at lower threshold, thus fully compensating for the loss of charge and resulting in a Signal to Noise ratio similar to the Gassiplex one.

Analysis of the data taken with APV and Gassiplex electronics was then performed using the distributions of reconstructed ring residuals, i.e. the difference between the expected ring radius, assuming the particle is a pion, and the radial distance of each cluster. The cut on cluster amplitude explained above was applied, as well as a simple cut requiring that the three consecutive amplitudes have increasing magnitudes. The background under the signal was determined by associating clusters of one event with tracks from the following event. The results show that the number of clusters in the peak using either APV or Gassiplex is the same, while the APV read-out reduces the background under the peak by about a factor of 5. A study of the signal shape by varying the trigger latency of the APV was also performed, indicating that the full width of the APV signal is 375 ns, in agreement with the 400 ns expectation.

A more detailed analysis of the signal shape given by the 3 consecutive samples allows us to determine the time of the hit with respect to the time of the trigger [12]. For large amplitudes a time resolution better than 15 ns is achieved, and even for the lowest amplitude range (over 3000 e$^-$), a time resolution better than 30 ns is observed. Owing to the purely exponential shape of the photon spectrum however, only 50% of the clusters have large enough amplitude to determine the time with a precision better than 30 ns.

The proposed APV read-out will be installed in the region not covered by the MAPMPTs, i.e 75% of the present RICH detector. In their final design, the front-end cards will house 4 APV chips mounted on separated smaller units for easier handling during bonding or in case of failure. Every four front-end cards will be read out by one ADC module, instead of three at present. Production of 63 000 channels of APV-based read-out system is foreseen for 2005, with an estimated cost of 5 Euro/channel, separated between 3 €/ch for the front-end cards and 2 €/ch for the ADC cards and GeSiCa. The total cost of the project is around 300 k€, about 60% of this amount is conditionally covered. For the remaining part, a submission of financing request is on-going. The system will be ready well before the start of the 2006 run in order to have enough time for commissioning.
5. THE RICH-1 UPGRADE PROJECT

The overall RICH-1 Upgrade project aims at further and significant increase of the RICH performances with the purpose of meeting the COMPASS experimental challenges in the years to come. In order to minimize the associated cost, two different technologies are proposed.

In the central region of the detector, where the hadron polar angles are small, both the photon detectors and the associated read-out electronics will be replaced. The use of MAPMTs for 25% of the total RICH surface, will lead to two major improvements. First, a wider photon detection wavelength region will be covered, allowing for a largely increased number of detected photons. As a result the kinematical domain where particle identification is possible will be increased towards both higher and lower energies. Furthermore, the increased number of photons will allow us to partially recover for the present reduced efficiency due to the photon screens present in the central region of RICH-1. Second, the much faster response of the read-out electronics with only a few ns time resolution should make the uncorrelated background level negligible; this features will not only increase the PID efficiency, but it will also have an extremely relevant impact on the ring resolution: with a strongly reduced background, the resolution is expected to scale with the square root of the number of detected photons.

In the larger external region of the detectors, covering 75% of the total surface, the present photon detectors will be coupled to a new, analog sampling read-out, based on the APV chip. With an order of magnitude better time resolution and dead time less architecture this read-out will significantly reduce the uncorrelated background level. In addition it will make the RICH-1 detector adequate for the higher beam intensities and high trigger rates.

We believe that this upgrade can push RICH-1 performances up to the limit that the instrument can reach, considering its effective length, its overall geometry and the characteristics of its radiator gas and its mirror system.

REFERENCES

1. COMPASS proposal